Effects of Statins on Angiogenesis and Vasculogenesis
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INTRODUCTION

Statins inhibit the activity of 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase, an enzyme that catalyzes mevalonate synthesis, the limiting step in cholesterol biosynthesis.1 The resulting reduction in intracellular cholesterol leads to a compensatory increase in cholesterol uptake by low-density lipoprotein (LDL) receptors and a decrease in plasma cholesterol. The discovery of the statins and their application in subjects with high cholesterol concentrations has made it possible to greatly improve the primary and secondary prevention of coronary artery disease.2,3 Recently, the effectiveness of the statins in the primary and secondary prevention of coronary artery disease has also been observed in subjects with lower cholesterol levels.4,6 Aside from reducing LDL cholesterol (C-LDL), the statins have a series of pleiotropic effects on several components of atherosclerosis, including endothelial function, cell migration, inflammation, and the thrombotic tendency of the plaque.7-12 In normocholesterolemic animals it has been demonstrated that statins have a protective effect against ischemia-reperfusion lesions of the cardiac muscle, probably through mechanisms related to nitric oxide production (NO) by endothelium.13

The serine/threonine protein kinase Akt or protein kinase B (PKB) is a multifunctional intracellular regulator of cellular survival, growth and metabolism 14 (Figure 1). In relation to its cardiovascular functions, Akt/PKB acts on the intracellular pathway stimulated by vascular endothelial growth factor (VEGF)14,15 and angiopoietin,16-18 promoting cell survival and ensuring adequate vascular development.19 Constitutive activation of Akt signaling protects cardiomyocytes against apoptosis in ischemia-reperfusion lesions.20 In addition to its cytoprotective effect, Akt acts as an activator of NO production by the endothelium in response to VEGF and shear stress through its capacity to phosphorylate the endothelial nitric oxide synthase (eNOS) in serines 1179 or 1177,21,22 thus controlling vasomotor tone.23 On the other hand, Akt is essential in the migration of endothelial cells to the VEGF-producing focus.24 Therefore, the capacity of Akt to mediate cell survival, NO production, and VEGF-induced migration suggests that protein kinase Akt can mediate endothelial response to angiogenic stimuli.
It has been demonstrated recently that the statins also stimulate the intracellular signaling pathway of protein kinase Akt/PKB\(^{25-27}\) in endothelial cells\(^{25}\) and the endothelial progenitor cells (EPC) of bone marrow,\(^{26,27}\) thus inducing both angiogenesis\(^{25}\) and vasculogenesis.\(^{26}\) The effects of the statins on the kinetics of EPC have also been demonstrated in humans by Vasa et al.\(^{28}\) This article reviews the effect of the statins on the induction of angiogenesis\(^{25}\) and vasculogenesis\(^{26}\) through mechanisms related with Akt activation.\(^{25-27}\)

**ANGIOGENESIS AND VASCULOGENESIS**

Angiogenesis and vasculogenesis are responsible for the development of the vascular system in the embryo\(^{29-32}\). Vasculogenesis is the process of blood vessel formation from endothelial progenitor cells (angioblasts) that migrate and fuse with other endothelial progenitor cells and differentiate into endothelial cells while forming new blood vessels. In contrast, angiogenesis is the process of the extension of the blood vessels that have formed by budding new capillaries through the migration and proliferation of previously differentiated endothelial cells (Figure 2).

It was initially thought that the vasculogenic process was restricted to embryonal development, whereas angiogenesis (which also occurs in the embryo) was the only process involved in neovascularization in adults. However, the paradigm of postnatal neovascularization was reviewed recently and it was discovered that

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**ABBREVIATIONS**

VEGF: vascular endothelial growth factor.
LDL: low-density lipoprotein.
NO: nitric oxide.
PKB: protein kinase B.
eNOS: endothelial nitric oxide synthase.
EPC: endothelial progenitor cells.
FACS: fluorescence-activated cell sorting, a flow cytometry technique.

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**Fig. 1.** Statins, Akt signaling and angiogenesis/vasculogenesis. Angiopoietin 1 (Ang-1), VEGF and fibroblast growth factor (FGF), when bound to their membrane receptors, induce the conversion of phosphatidylinositol 4,5-biphosphate (PIP2) to phosphatidylinositol 3,4,5-triphosphate (PIP3) by phosphatidylinositol 3-kinase (PI3K). PIP3 formation is necessary for the phosphorylation of Akt protein kinase by PDK-1 kinase. Statin treatment increases the phosphorylation of Akt, while wortmannin (a PI3K inhibitor) prevents it. Mevalonate, the product of HMG-CoA reductase, also inhibits PI3K and the subsequent phosphorylation of Akt. Therefore, the statins, by inhibiting HMG-CoA reductase and the production of mevalonate, increase Akt phosphorylation and, at the same time, the phosphorylation and activation of endothelial nitric oxide synthase (eNOS), nitric oxide synthesis (NO), and a variety of physiological effects induced in angiogenesis and vasculogenesis. Akt also prevents endothelial cell apoptosis.
endothelial progenitor cells circulating in peripheral blood, are incorporated by neovascularization foci in adult animals, they increase in number in response to tissue ischemia, and they promote the development of collateral blood vessels after their expansion in vitro and later transplantation. These studies have established that both angiogenesis and vasculogenesis are responsible for neovascularization in adults.

A third mechanism that probably contributes to the development of collateral vessels is the increase in the size and caliber of pre-existing arteriolar collateral connections, a process called arteriogenesis. The presence and number of these native collateral vessels vary widely between individuals and species. When a vessel becomes occluded, there is an increase in the velocity of blood flow through pre-existing collateral vessels and an increase in luminal shear stress, factors that contribute to the maturation of the collateral vessels, particularly those of intermediate size.

Methods of study in vitro

The development of techniques for the culture of endothelial cells has made it possible to understand the processes involved in angiogenesis. Endothelial cells in culture retain the capacity to respond to factors that stimulate or inhibit angiogenesis as well as the capacity to form endothelial tubes in vitro. Assays of cellular proliferation allow the effect of a certain substance on endothelial cell proliferation to be analyzed. The migration of endothelial cells toward a solution containing a certain substance, separated by a permeable membrane, can be examined in a Boyden chamber. The mechanisms of tubular endothelial formation and the effect of a certain substance on tubules can be studied using two-dimensional or three-dimensional assays. With these techniques, the processes of formation of the endothelial lumen and the influence of the extracellular matrix on capillary development are analyzed. Finally, cultures of endothelial cells allow the study of the molecular pathways involved in angiogenesis processes.

Recently, by using cell selection techniques and special culture media, techniques developed to study differentiated endothelial cells have been used to study endothelial progenitor cells.

Methods of study in vivo

Although techniques in vitro enable a preliminary analysis to be made of angiogenesis and vasculogenesis, many factors that can influence or modulate these processes in vivo. In order to study the mechanisms of blood vessel formation in vivo, different biological
systems have been developed to quantify or demonstrate the effect of a certain substance: mouse cornea models, chicken embryo chorioallantoic membrane, or spongy implants.38 These systems require the sacrifice of the animal so they only capture the effect in a specific moment. In order to study the temporal evolution of events in a single tissue, intravital microscopy techniques have been developed for the skin on the back or skull of the mouse.39 Finally, the development of genetic engineering techniques has made it possible to study the effect of the suppression (knock-out) or addition (knock-in) of a gene to the processes of vasculogenesis and angiogenesis.

The study of postnatal vasculogenesis and the effect of certain substances on vasculogenesis processes has been possible thanks to the use of a flow-cytometry techniques, fluorescence-activated cell sorting (FACS), special techniques for culturing endothelial progenitor cells (EPC) from peripheral blood, and murine bone marrow transplantation models.33-36 FACS is used to detect and quantify EPC in peripheral blood using antibodies against the surface antigens of these cells. The influence of drugs or growth factors on the number of these cells in peripheral blood can be analyzed this way. The special techniques of cell selection and culture developed by our group have also made it possible to detect and quantify EPC. In the murine model of bone marrow transplantation, bone marrow cells from a mouse donor are transplanted to a mouse receptor with a gene that encodes the elaboration of a substance that allows it to be detected later (Figure 3).

Fig. 3. Murine model of bone marrow transplantation for the study of vasculogenesis. The bone marrow donors used are transgenic mice that constitutively express the gene LacZ (which encodes beta-galactosidase) regulated by a specific endothelial promoter, Tie-2. The bone marrow is extracted and transplanted to a mouse receptor whose bone marrow has been sublethally irradiated. After a period of 4 weeks to achieve the reconstitution of the transplanted bone marrow, one or more interventions are made in the mouse receptor (the case shown is a corneal model) to stimulate neovascularization. After these interventions, the animals are sacrificed and a histological study is made to detect beta-galactosidase expression. With X-GAL stain, cells that express beta-galactosidase acquire a bluish color. The use of a specific promoter for endothelial cells allows the blue cells that have been incorporated into neovascularization foci to be identified as cells of endothelial lineage.

In these cells, statins increased the proliferation and migration, as well as the formation of the vascular structure. In addition, the inhibition of Akt by statins stimulates the intracellular signaling pathway of the protein kinase Akt/PKB,25-27 which promotes both angiogenesis and vasculogenesis.26 In addition, Vasa et al also have been able to demonstrate in humans the effects of statins on the kinetics of EPC.28

**EFFECT OF STATINS ON THE INDUCTION OF ANGIOGENESIS AND VASCULOGENESIS**

Investigations made in our laboratory and elsewhere have demonstrated that the statins stimulate the intracellular signaling pathway of the protein kinase Akt/PKB,25-27 which promotes both angiogenesis and vasculogenesis.26 In addition, Vasa et al also have been able to demonstrate in humans the effects of statins on the kinetics of EPC.28

**Effects in vitro of statins**

The statins rapidly activate protein kinase Akt/PKB in endothelial cells25 and EPC,26,27 thus increasing the phosphorylation of eNOS and the subsequent production of NO. Akt activation by statins promotes the proliferation, migration, and cellular survival of endothelial cells and EPC, as well as the formation of the vascular structure. In addition, the inhibition of Akt by the use of adenovirus that encode dominant negative forms of Akt causes inhibition of the effects induced by statins. The potential of statins in tissue regeneration processes was demonstrated earlier in osteoblasts. In these cells, statins increased the proliferation and level of activity, consequently increasing bone formation.40

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Although the mechanisms of Akt activation by statins are not accurately known, it is probable that phosphatidylinositol 3-kinase (PI3K) signaling is involved because this process is blocked by wortmannin and LY294002, two inhibitors of the enzyme (Figure 1). In addition, the inhibition of HMG-CoA reductase is necessary, since the activation of Akt by simvastatin was inhibited by the addition of mevalonate to incubation (Figure 1). Mevalonate is necessary, not only for the biosynthesis of cholesterol, but also in the production of ubiquinone, dolichols and isoprenoids, which are essential in several cell processes. Although the statins stabilize the messenger RNA (mRNA) of eNOS by modifying isoprenoid synthesis, we did not observe changes in protein synthesize eNOS values. In this sense, it is important to emphasize that the increase in mRNA concentration was later (24 h) than the activation of eNOS phosphorylation by Akt (15 min). This shorter activation time is consistent with the changes induced by statins in the production of NO and in the vasodilation observed in aortic anuuli ex vivo.

Effects in vivo of statins

The statins and activation of intracellular Akt signaling promote angiogenesis in models of peripheral ischemia developed in normocholesterolemic rabbits. In animals that received statins, higher perfusion pressures, a larger number of collateral vessels, and a greater capillary density were observed (Figure 4). On the other hand, the statins increase the number of endothelial progenitor cells in peripheral blood in both mice and humans. In addition, the statins increase corneal neovascularization in normocholesterolemic mice, in part due to vasculogenesis from EPC obtained from bone marrow (Figures 3 and 5). Using the murine model of bone marrow transplantation, it was possible to demonstrate a greater number of EPC from bone marrow in the corneas of mice treated with statins. Therefore, statins have an important effect on EPC kinetics, as had been demonstrated previously with VEGF or granulocyte and monocyte-colony stimulating factor (GM-CSF), and statin-induced mobilization of these cells could increase postnatal neovascularization.

CONCLUSIONS

Statins promote the proliferation, migration, and cellular survival of endothelial cells and EPC obtained from bone marrow through mechanisms related to the activation of serine/threonine protein kinase Akt or...
PKB. In a way similar to VEGF, statins promote angiogenesis and vasculogenesis. Therefore, Akt activation can be responsible for some of the beneficial effects of statins, including postnatal neovascularization.

REFERENCES

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